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Circular Electron Beam Radiation Sources

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13. ABSTRACT *(Maximum 200 words)*

Azimuthally periodic magnetic structures based on magic sphere and magic toroid configurations afford the possibility of free electron radiation sources in which the electrons oscillate about circular rather than the usual rectilinear trajectories. In such structures radiation from the electrons is generated over multiple circuits rather than over the single pass of the conventional lasers. Azimuthally periodic teeth in the core of both toroid and sphere enable the resulting periodic field to confine the electrons to a circular orbit and to cause it to oscillate radially at right angles to that orbit. Computer calculations for sample structures show respective mean orbital fields of 3.5 T and 2.4 T for sphere and toroid, while the field ranges between maximum and minimum are 0.3 T and 1.2 T, respectively.

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INTRODUCTION

In recent years there has been considerable interest in the employment of permanent magnets to provide to electron beams accelerations that cause them to radiate.[1] Many of these fields are periodic to cause electrons to undergo oscillatory accelerations transverse to the beam axis to produce the desired frequencies. Examples are synchrotron sources wherein the periods are those of circular electron orbits, wigglers in which the periods are those of sinusoidal or quasi-sinusoidal magnetic structures and twisters wherein the fields are constant in magnitude but rotate with progression along the beam axis. Because of the unusually high fields they provide for their structural masses the magic sphere and cylinder (Figure 1)[2,3] seem attractive field sources for both wiggler and synchrotron arrays in which the mean electron paths are circular rather than rectilinear. This provides the advantage of long electron paths over which the electron kinetic energy can be extracted in the form of radiation without the inconvenience of unduly long structures.

TOROIDS

The toroidal structure is the volume traced when a cross section of a magic ring is revolved about an axis external to itself as in Figure 2A. The field produced in the interior is, for practical purposes, the same as that of a magic cylinder. If the cavity is filled with iron or another soft magnetic material and an equatorial slot is cut to accommodate a circulating electron beam, a basis for a synchrotron radiation source results as in Figure 2B. If the iron core is grooved or arranged azimuthally in equally spaced teeth as in Figure 3, the resulting periodic field causes wiggler radiation. For a structure in which the principal radius, R, is 12 cm and the inner r_i and outer r_o radii of the toroidal section are 1 and 4 cm, respectively, the internal field is 24 kG if the magnet material has a remanence, B_r, of 12 kG. Such a structure would provide synchrotron radiation with a fundamental frequency f_s of 8 x 10^{13} Hz from a relativistic beam of 9 x 10^7 eV. If the grooved iron core has an azimuthal period of $\pi/4$, wiggler radiation of frequency 8 f_s = 6 x 10^{14} would be emitted. If the beam slot width is 3 mm, the field oscillates between 1.8 T and 2.9 T which are the values between the grooves of the serrations and between the iron "teeth," respectively.

In such a structure, the electron beam energy is chosen so that the mean field of 2.4 T will keep electrons of energy 9 x 10^7 eV on the circle of radius 12 cm, the center of the toroidal section. But as the field is azimuthally periodic, its value when passing radial grooves will be smaller than when between the iron ridges. In the former case the field will be less than $\overline{B}$ and hence too small to keep an electron on its mean circular path, causing it to drift radially outward. When the electron passes by the

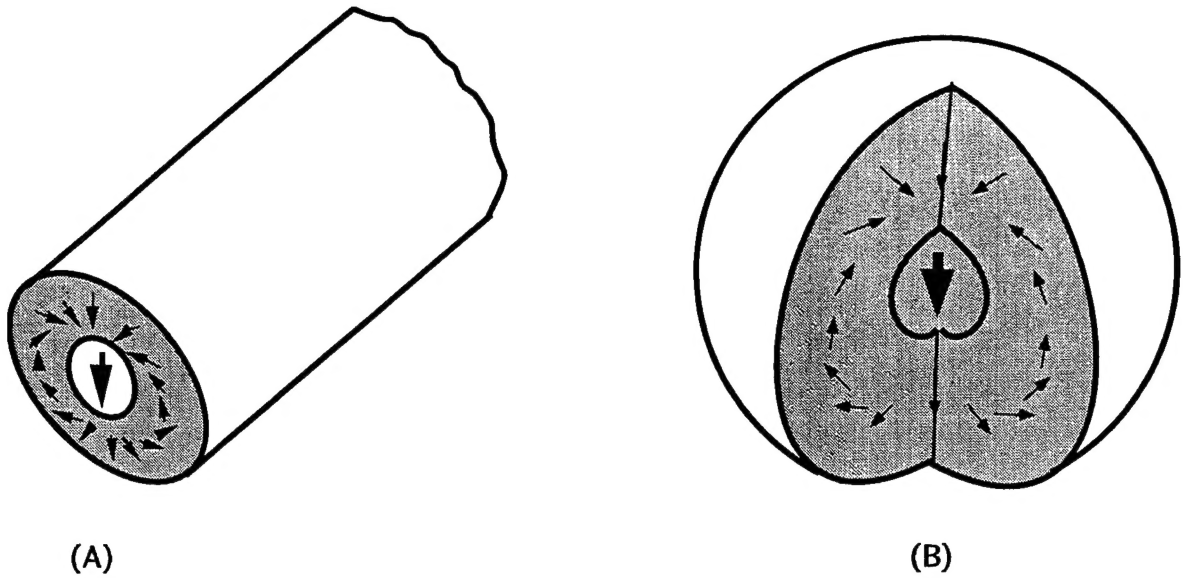

Figure 1. (A) Magic ring and (B) magic sphere. Small arrows show the direction of magnetization, large arrow indicates direction of magnetic field generated in the interior cavity.

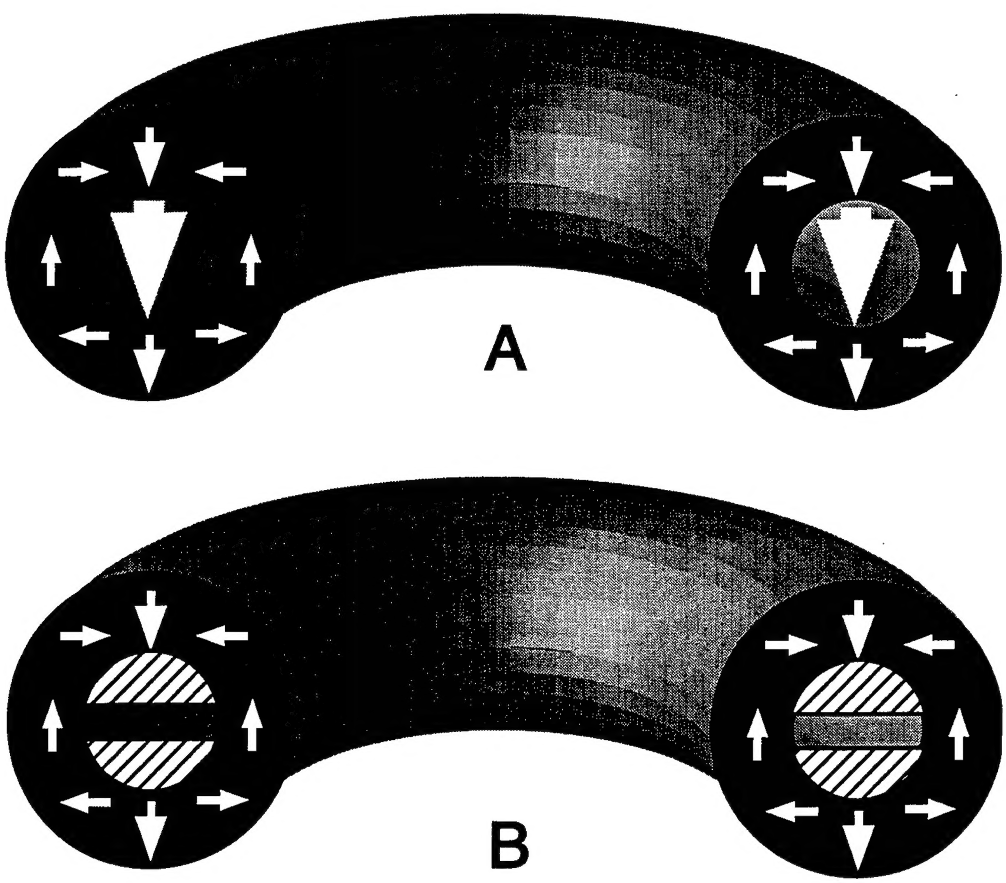

Figure 2. Magic toroids (A) with circular cavity, (B) with iron core divided by equatorial beam slot.

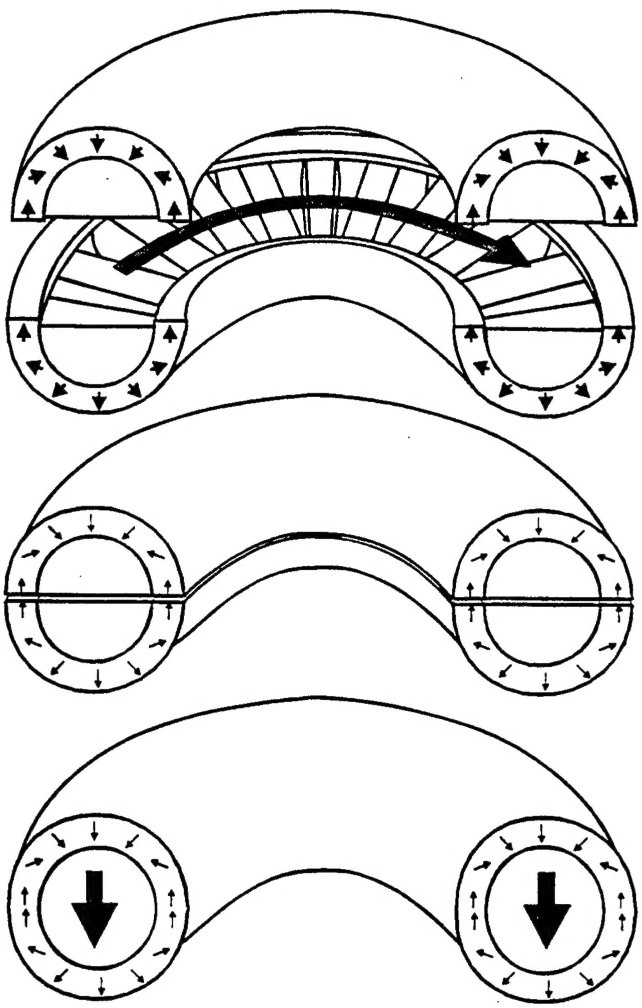

Figure 3. Magic toroid with a core of azimuthally spaced iron teeth.

ridges, the field will be larger than $\overline{B}$, causing the electron to be drawn inward beyond the mean path. Hence the electron "wiggles" about the mean circle and radiates, behaving like a circular wiggler. The central angular frequency of this radiation would be

$$\omega = N\omega_s$$

where N is the number of grooves in a circuit. Superposed on the wiggler radiation would be the "synchrotron" radiation of fundamental frequency $\gamma e\overline{B} / mc$. The radiation is in a tangential direction so that an equatorial slit could be cut in the outer periphery of the toroid to provide exit for the radiation. Then both synchrotron and wiggler radiation would form a tangential radiation pattern in the equatorial plane. Should unidirectional beams be desired, toroids could be used to create a "race-track" shaped structure wherein two parallel rectilinear lasers are joined at their ends by semi-toroids in which the iron cores are ungrooved. Then synchrotron radiation would be generated in the toroids and wiggler radiations in the two rectilinear parts of the structure in which any standard wiggler structure is employed, e.g., magic ring slices that alternate in polarity with progression along the wiggler axis.

SPHERES

The structures based on magic spheres are capable of producing much higher fields than those based on the toroids, but in practice the radii of electron-beam orbits are also smaller and higher fields are needed to maintain the mean orbit for a given electron energy. Were orbits of equal radius practical for both sphere and toroid, the sphere could, of course, accommodate higher electron energies and correspondingly higher radiation frequencies. We analyzed a sphere for which r_o = 12.5 cm, and r_i = 2.5 cm and B_r = 14 kG. Figure 4 shows a section of the sphere which has an azimuthally periodic core of period $\pi / 4$, and Figure 5 shows the azimuthal periodicity of the field such a structure produces. The field ranges from 3.4 T to 3.7 T causing synchrotron radiation of 2.5 x 10^{13} Hz and wiggler radiation of 2.0 x 10^{14} Hz.

The toroids have the advantage of having greater azimuthal field contrast ΔB between maxima and minima. Since it is half this difference that determines acceleration, a, with respect to the mean orbit, and since the radiated energy is proportional to the square of the acceleration, the toroid radiates the greater power, all other things being equal.

RADIAL FIELD VARIATION

The field in the working slot varies radially in both the spheres and the toroids; more markedly in the former. This can be ameliorated by a radial shaping of the iron surfaces.

CONCLUSION

Magic spheres and toroids offer higher accelerating fields, up to several Tesla, in contrast to the hundreds or few thousands of Gauss generally available in the conventional permanent magnet structures. Also, the circular orbits of the electrons afford more thorough extraction of radiant energy from the electron beam. For pure synchrotron use of the magic sphere, fields of about 4 T are not impracticable. While these structures have attractive features, further research is necessary to make them practical. One problem is that of confinement of the beam to the equatorial plane. In the case of the toroid, this may be accomplished by solenoidal electrical windings wound about its circular section. In the case of spheres, perhaps the iron core faces can be shaped to bend the lines of force, so that they provide a restoring force. Partial access and production of undulator action in circular beam paths may also be nontrivial problems.

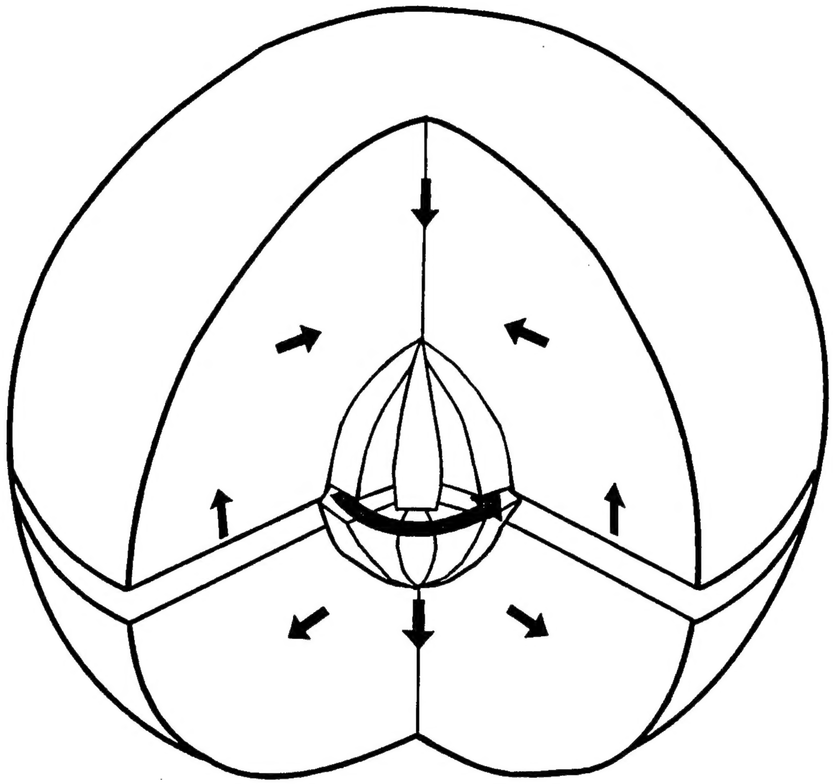

Figure 4. Section of magic sphere with an iron core of azimuthal periodicity.

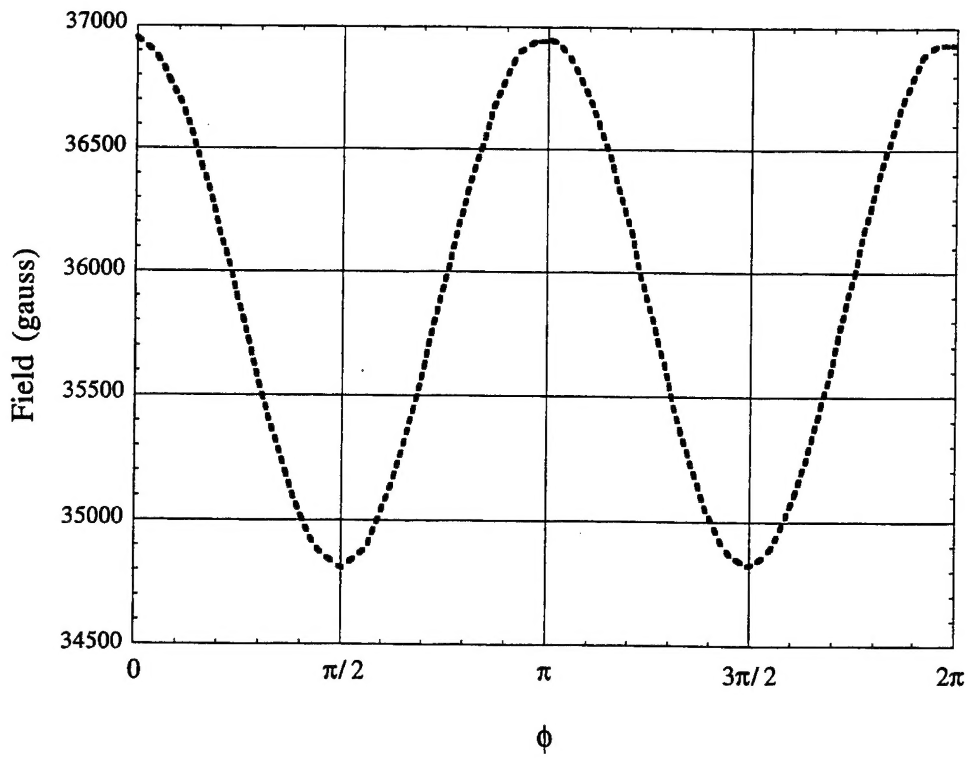

Figure 5. Field periodicity generated in the sphere of Fig. 4.

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